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Federal regulations concerning the generation and release of many gaseous pollutants, including NOxs, are becoming increasingly more stingent. A number of diverse military operations generate large amounts of NOxs on an episodic basis. Therefore, themilitary is motivated to acquire new pollution control technologies that will bring them into compoliance with the evolving more stringent regulations. Non0thermal plasma (NTP) devices and their variants- such as hybrid systems- offer attractive alternatives to more traditional acid gas (SOx and NOx) control approaches. such as scrubbers, catalytic systems, or adsorbers. The higher performance that is possible with NTP-based pollution control systems comes at a price of complexity and cost. Widespread use of NTP-based pollution control technology by the commercial or military sectors will occur only when the economics for such systems are favorable compared to competing technologies. This paper identifies and discusses the many factors that cause uncertainly in the economic analysis of NTP-based reactors for NOx control. In particular, we focus on conditions representative of jet-engine exhaust containing nitric oxide (NO) combined with hydrocarbons in an emission stream that is primarily air.

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Factors and Uncertainties that Impact Economic Assessments of Non-Thermal Plasma Based Devices to Control NO_x Generated from Jet Engine and Cruise Missile Test Facilities

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Abstract- Federal regulations concerning the generation and release of many gaseous pollutants, including NO_xs, are becoming increasingly more stringent. A number of diverse military operations generate large amounts of NO_xs on an episodic basis. Therefore, the military is motivated to acquire new pollution control technologies that will bring them into compliance with the evolving more stringent regulations. Non-thermal plasma (NTP) devices and their variants- such as hybrid systems- offer attractive alternatives to more traditional acid gas (SO_x and NO_x) control approaches such as scrubbers, catalytic systems, or adsorbers. The higher performance that is possible with NTP-based pollution control systems comes at a price of complexity and cost. Widespread use of NTP-based pollution control technology by the commercial or military sectors will occur only when the economics for such systems are favorable compared to competing technologies. This paper identifies and discusses the many factors that cause uncertainty in the economic analysis of NTP-based reactors for NO_x control. In particular, we focus on conditions representative of jet-engine exhaust containing nitric oxide (NO) combined with hydrocarbons in an emission stream that is primarily air.

I INTRODUCTION

A. Conventional de-NO_x Technologies

The process of combustion, using a fuel such as coal (in a coal-fired electrical power plant) or diesel fuel (in diesel engines, including jet engines) can generate substantial quanties of oxides of nitrogen (NO_X) and sulfur (SO_X). SO_X emissions can be easily controlled by using low-sulfur-content fuels. However, NO_X emissions still pose a problem and we are concentrating on emissions from jet-engine test cells (JETCs) and Cruise Missile test cells (CMTCs), which also employ jet engines, albeit smaller ones.

A1. Conventional Activated Carbon Adsorbers

A very common post-combustion air-emissions control technique (for NO_X and other compounds) is to pass an exhaust stream through an adsorber system, thus capturing the entrained pollutants. Granular activated carbon (GAC) is the most commonly-employed adsorber medium for many air pollutants because it has a relatively low capital cost, has a very high surface area to volume ratio, and can adsorb a wide variety of compounds (Cummings & Booth 1996 [1], Vercammen et al 1997 [2]). However, when the GAC loses its ability to easily adsorb pollutants, it must be regenerated, reactivated, or disposed of as waste. In the processes of regeneration or reactivation, heated gases and/or steam are usually employed to desorb or strip the pollutants from the granules. These processes usually do not restore all of the adsorption capacity and the GAC must eventually be replaced, typically within five to ten cycles. If hazardous chemical pollutants are involved, handling, transportation, and permitting issues come into play - which can significantly increase costs. In summary [1, 2], GAC has the following properties:

- Simple and inexpensive at low exhaust-gas flow rates and low pollutants concentrations
- Can be used as a concentrator and, if product is recovered, this can offset the annual operating cost
- Desorbed compounds require ultimate disposal or further treatment
- GAC cartridges are sensitive to plugging and poisoning (deactivation)
- GAC must be periodically regenerated; at moderate to high flow rates and pollutant concentrations, the costs of off-site regeneration tend to outweigh the advantages of simplicity of use
- The adsorber deactivates over time
- The cost of treatment largely depends on the pollutant concentration
- GAC is best suited for short-term, low mass-flow applications
- GAC adsorber equipoment has a relatively high pressure drop
- Over a 10-year life cycle, about 90% of the cost of a GAC system is associated with operating expenses.

A2. Conventional Catalytic Systems

For post-combustion NO_X control, the best presently available technologies (from a summary by Penetrante 1993 [3]) are Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), RAPRENOx, and Non-Selective Catalytic Reduction (NSCR). SCR, which has been under development for over thirty years, employs ammonia injection into the emissions stream and the subsequent reduction of NO to N_2 on a catalyst. SNCR, which has been used for almost 25 years, does not use a catalyst but employs a combination of ammonia or urea-based reducing reagents and higher operating temperature (~ 370 C). The RAPRENOx process is similar to SNCR and surface catalysis; however, it uses isocyanic acid, rather than ammonia or urea, as an additive. NSNR uses hydrocarbon additives to reduce NO in the presence of a catalyst and was developed over fifty years ago. Choosing a process can be quite complicated because of a strong dependence on the particular characteristics of the combustion unit.

Because these conventional de-NO_X processes must be closely matched to the combustion device, sometimes make use of high-temperature catalysts (which suffer sulfur poisoning, deterioration), and are often quite complicated and expensive, searches for newer technologies have been undertaken during the past 20 or 25 years. Some of the most promising of the emerging technologies are based on NTP methods.

II EMERGING DE-NO_x TECHNOLOGIES - NTPs

The roots of treating hazardous and/or toxic chemicals with NTPs go back over two decades to military applications for destroying toxic chemical warfare agents with electric discharge reactors and civilian applications for treating flue gases (SO_X and NO_X) from electric power plants and other installations (e.g., steel mills) with electron beams.

The first civilian applications of NTPs for pollution control were focused on the removal of oxides of nitrogen and sulfur (NO_X, SO_X) with electron-beam reactors. The scrubbing of flue gases with electron-beam systems was initiated in 1970 in Japan by the Ebara Corporation (Frank & Hirano 1993 [4]) and extensively studied during that decade by Japanese scientists (Kawamura et al 1978 [5]), and, later, by others (Pearson & Ham 1988 [6]). A study on the decomposition of an organic compound (vinyl chloride) was published in the early 1980s by Slater & Douglas-Hamilton 1981 [7] and, more recently, extensive work on VOCs has been done by the Karlsruhe group (Paur et al 1993 [8]).

Based on laboratory and small-scale studies of de-SO_X and de-NO_X, pilot plants and larger demonstration facilities were constructed and tested in Japan, the United States, and Germany (Kawamura et al 1979 [9], Frank et al 1987 [10], Fuchs et al 1987 [11], Jordan & Schikarski 1987 [12]). Chemical models to describe the process in reasonable agreement with experiments were first published by (Tokunaga et al 1984 [13], Busi et al 1985 [14], and Matzing 1991 [15]). Unfortunately, for the early scale-up demonstrations, a lack of commercial acceptance and unfavorable economics (especially the capital and maintenance cost of electron accelerators at that time) compared to conventional systems contributed to a loss of interest in the technology. This interest seems to have been renewed recently, as evidenced by the construction and operation of large-scale flue-gas treatment facilities in Europe (Chmielewski et al 1995 [16]).

The removal of SO_X and NO_X from gaseous media was also investigated at laboratory scale

using electrical-discharge reactors (pulsed corona) in the 1980s - with pioneering experimental work performed for NO_X by Masuda & Nakao 1990 [17] and for SO_X by Mizuno et al 1986 [18]; and modeling work performed by Gallimberti 1988 [19]. Following these basic investigations, scale-up of the pulsed corona process for flue gases emitted from a coal-burning electrical power plant was carried out at pilot-plant and demonstration levels (Dinelli et al 1990 [20], Civitano et al 1993 [21]). The larger pilot-plant demonstrations appeared to show favorable economics ([21], Tamaki et al 1998 [22], Song et al 1997 [23]).

Several non-thermal plasma technologies for de-NO_X are in the commercialization stage and, more recently, several small scale commercial pulsed corona and e-beam systems have become operational (Li et al 1998 [24], and a full-scale, flue-gas demonstration unit which is under construction by Chubu Electric Power in Japan for a 220 MW power plant). Economic evaluations are needed not only for the selection of the best-matched technology for the operating facility, but also for providing guidance for future research and development on those technologies. In this paper, we show that present NTP-based processes are currently showing favorable economic trends.

It should be noted that NH_3 and hydrocarbons (HCs) can also be added to change the final product distributions of the effluent gas. Adding HCs and NH_3 also enhance reductive chemical paths via NH and NH_2, but the majority of NH_3-related chemistry forms aerosols by surface oxidation chemistry of NH_4NO_3.

III JET ENGINE EXHAUST STREAM

There are several studies and reports that address jet-engine emissions arising from engine test facilities (Spicer et al 1988 [25], 1990 [26]; Walker 1996 [27]). Table 1 shows a summary emissions inventory for Tinker AFB JETCs 1-12 for the year 1995; when 3,414,836 gallons of JP-5 fuel were consumed in a time period of 4420 hours of operation [27]. The emissions were calculated on the basis of fuel consumption but not directly measured. Means of calculating inventories for air pollutants arising from such sources have been formulated and documented by Jagielski et al 1994 [28].

Table 1: Calculated emissions inventory for twelve JETCs at Tinker AFB for CY1995.

Compound	Emission Inventory (ton/yr)
NO_x	113.01
SO_x	30.71
Aggregate hydrocarbons	100.45
CO	156.34
Particulates	26.72
PM-10	4.45

IV HISTORICAL COST ANALYSIS

Few works in the past dealt with the economic evaluation of NTP air-pollution technologies. One past economic evaluation carried out by the Japanese Mechanical Industry Association and Energy Engineering Institute (Masuda 1993 [29]) compared three types of de-SO_X and de-NO_X facilities for a coal-fired power plant - the conventional, combined wet-scrubber - selective catalytic reduction process, the electron beam process, and the pulsed corona process. The results of this study (for a 250 MW power plant) showed that the pulsed corona process was more economical than the others. Most other works have been on electron beams (Frank & Hirano 1993 [4], Frank 1993 [30]) or pulsed corona (Civitano 1993 [21]). Bartoszek at al, 1998 [31] outlined economic evaluation methods for advanced reburning de-SO_X and de-NO_X processes based on thermal and non-thermal plasmas and used the energy yield (removed amount of acid gas g / input power kWh) as a figure of merit for the economic evaluation of plasma processes.

The work of Frank [30] pointed out that cost analyses of e-beam de-NO_X have been carried out by several groups and that it is extremely difficult to compare the various estimates because different assumptions have been made by those carrying out the work. Primary among the assumptions is the cost of the heart of the system: the electron-beam accelerator. As of 1992 (with assumptions about the development of lower-cost, modular accelerators), an estimate of $200/kW of power plant output is proposed for an installed

flue-gas de-SO_X/NO_X system on a 500 MW power plant module. This is based on an accelerator cost of $2/W and a $50/ton by-product credit (gypsum and/or fertilizer). Frank concluded that such a cost makes e-beam de-NO_X cost competitive with more conventional processes. Frank & Hirano [4] also refer to a study conducted by the Electric Power Research Institute (EPRI) and subcontractors (Radian Corp. and Sargent & Lundy) that evaluated over 70 processes for air pollution control. The e-beam process was highly rated for combined SO_X/NO_X removal: the EPRI report stated, that for power plant flue-gas treatment retrofits, the e-beam process was rated as equivalent or preferable to the combined Flue Gas Desulfurization (FGD)/Selective Catalytic Reduction (SCR) process - the most often employed flue-gas treatment method at that time (and, largely, still the case).

For the pulsed corona process, Civitano et al [21] calculate the cost for a de-SO_X/NO_X flue gas system to be installed on a 320 MW power plant. However, they do not compare the cost with conventional technologies but simply state that it is less expensive. Other studies on the economics of de-NO_X by pulsed corona (Haythornthwaite et al 1997 [32]) have concluded that, using a spark gap-switched pulsed corona reactor (which converts NO to higher oxides of nitrogen that are treated by a sodium thiosulfate wet scrubber) the cost of such a system is unreasonable for a full-scale JETC (e.g., ~ $17 M per year operation and maintenance cost for 50 hours of operation per week). Clearly their conclusion about direct pulsed corona (PC) treatment of the exhaust stream, followed by wet scrubbing, is reasonable (as demonstrated by subscale and field tests). Therefore, we conclude that other architectures, as suggested in this paper, should be considered instead. Studies of the economics of de-NO_X by dielectric barrier discharges (silent discharge plasma) are very rare at scales larger than benchtop. However, a commercial modified dielectric-barrier system that shows promising cost projections for flue-gas treatment has recently been developed and fielded by Bittenson and Breault [34]. Recently, a promising, novel corona reactor called the Corona Radical Shower (CRS) or radical injector, that employs a small NTP reactor to inject beneficial active species into the main NTP reactor, has been demonstrated by Chang et al [35].

Historically, in formulating costs for NTP de-NO_X and comparisons with other technologies (even one type of NTP with others), there are "apples & oranges problems", i.e., workers did not use consistent measurement techniques and parameters. This makes it hard to compare one plasma system with another and with conventional methods. We will do the best we can in making comparisons using the best available interpretable data. Our practice will be to use the plasma energy density (and the associated electrical coupling efficiency from power supply to plasma) and the removal fraction of the pollutant as key parameters in the analyses.

The non-thermal plasma (NTP) techniques are still not optimum and economic evaluations for commercial plants are rare. However, more recently, Kim & Chang 1998 [33] estimated the economics as closely as possible by using up-to-date information. The most important objective of an economic evaluation is to decide which system is most effective for the given conditions in terms of the flow rate of exhaust gas, initial concentration of NO_X, SO_X, *other emissions,* and facility requirements.

V ECONOMIC MODEL

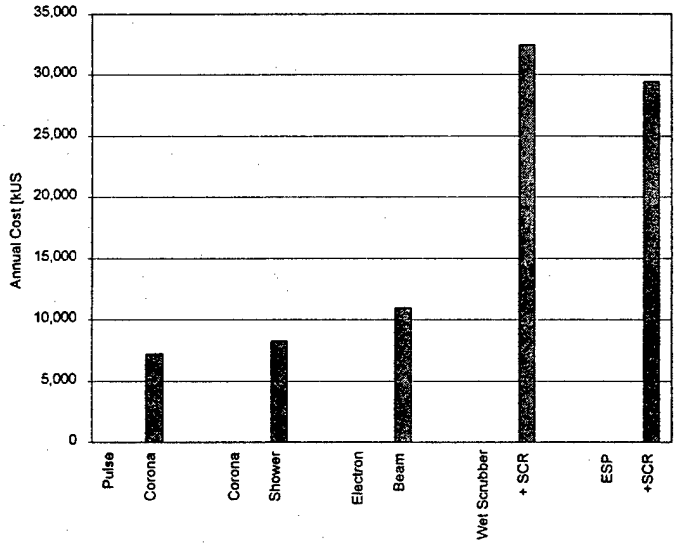
The computer code (SUENTP) to predict scale-up and economic evaluation of several eligible non-thermal plasma processes for air pollution control - electron beam process, pulsed corona process, and corona radical shower process - was developed for a commercial power plant [33]. The data obtained from pilot-plant tests are input with general data to provide information for the conceptual design of scaled-up commercial plants. The economic evaluation procedure deals with the total capital investment and the total annual cost. The total capital investment comes into the indirect annual cost as the item of capital recovery. The levelized cost and the levelized busbar cost are also calculated. In the Kim & Chang paper [33], an example calculation is presented to evaluate the cost of three non-thermal systems and the results compared with a conventional wet-scrubber/selective catalytic reduction combined system.

Several eligible non-thermal plasma

technologies are in the stage of commercialization and, more recently, several small scale commercial systems based on pulsed corona and electron beam are operating (Tamaki et al 1998 [22], Song et al 1997 [23]), Li et al 1998 [24]). Economic evaluations are needed not only for the selection of the best-matched technology for the operating facility, but also for providing guidance for future R&D on those technologies and to provide guidance to the DoD on viable, alternative NTP air-pollution control technologies.

Non-thermal plasma technology for emissions control is very complicated in terms of both physical and chemical phenomena, so it is difficult to analyze theoretically. Therefore most design data should be obtained from experimental studies. In the model work, the principal design data are acquired from pilot-plant experiments. Then these data are adopted as design data for commercial plants.

Figure 1 shows a comparison of three plasma systems with conventional technology for model emissions for a JETC with an exhaust flow rate of $1.7x10^6$ Nm^3/h ($1.0x10^6$ SCFM).



Gas Flow Rate: 1.70 x 10^6 Nm^3/h (1.0 x 10^6 SCFM)

(k$)	Pulsed Corona	Corona Shower	Electron Beam	Wet Scrubber + SCR	ESP + SCR
Capital Recovery	3,594	4,151	6,504	3,802	3,123
Labor & Maintenance	1,823	2,060	3,061	4,641	4,641
Electric Power	1,674	1,970	1,318	2,082	1,403
Chemicals & Utilities	110	110	110	21,935	20,247
Total Annual Cost	7,139	8,230	10,931	32,459	29,414
Fertilizer Recovery	62	62	62	0	0

Figure 1: Comparison of three plasma systems with conventional technology for a JETC with an exhaust flow rate of $1.7x10^6$ Nm^3/h ($1.0x10^6$ SCFM).

Although not disclosed in these figures, the costs of the electron accelerator and pulse generator comprise the majority of the total capital costs of the EB process, the PC process, and the dielectric-barrier process, respectively. However, the DC power supply was not the main part of the CS process capital cost because it is much less expensive (by factors of 2-10) than an electron accelerator or a pulse generator. The most outstanding parameter which affects both the capital cost and operating cost is energy yield. High energy yield implies a need for a lower capacity power supply and less electric power consumed. This is another reason that the corona shower process has the lowest total annual cost, including capital recovery. The total annual cost of a pulsed corona system is almost the same as an electron beam system. Both systems have slightly higher than the half of the total annual cost of a conventional combined system.

VI CONCLUSION

Many of the papers describing NTP treatment of air emissions present performance description which is phenomenological and, consequently, do not provide a consistent way to compare the scaling and optimization properties of different NTP reactors. In this paper we have attempted to present a simple basis for comparing different types of NTP reactors, based on the concept of: the plasma specific energy (electrical energy per unit volume deposited in the reactor active volume) required to remove a particular pollutant to a prescribed level in a defined exhaust-gas mixture and the associated yield (electrical energy cost per mass of pollutant removed).

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